Thermal Testing of Thermal Protection System (TPS) Materials

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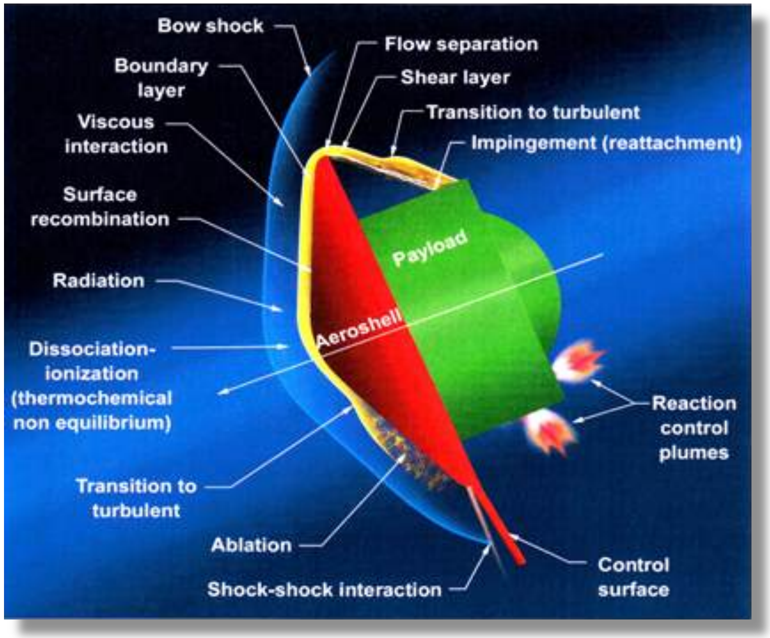
Outline

- Introduction to Thermal Testing of TPS Materials
  - Atmospheric Entry Review & Challenges
  - Need for Piecewise Testing
- Test Facilities
  - Arc Jets
  - LASER (LHMEL)
  - Solar Tower
  - Shock Tube
  - Ballistic Range
- Summary

Atmospheric Entry Review

- Atmospheric entry vehicles require thermal protection systems (TPS) because they are subjected to intense heating



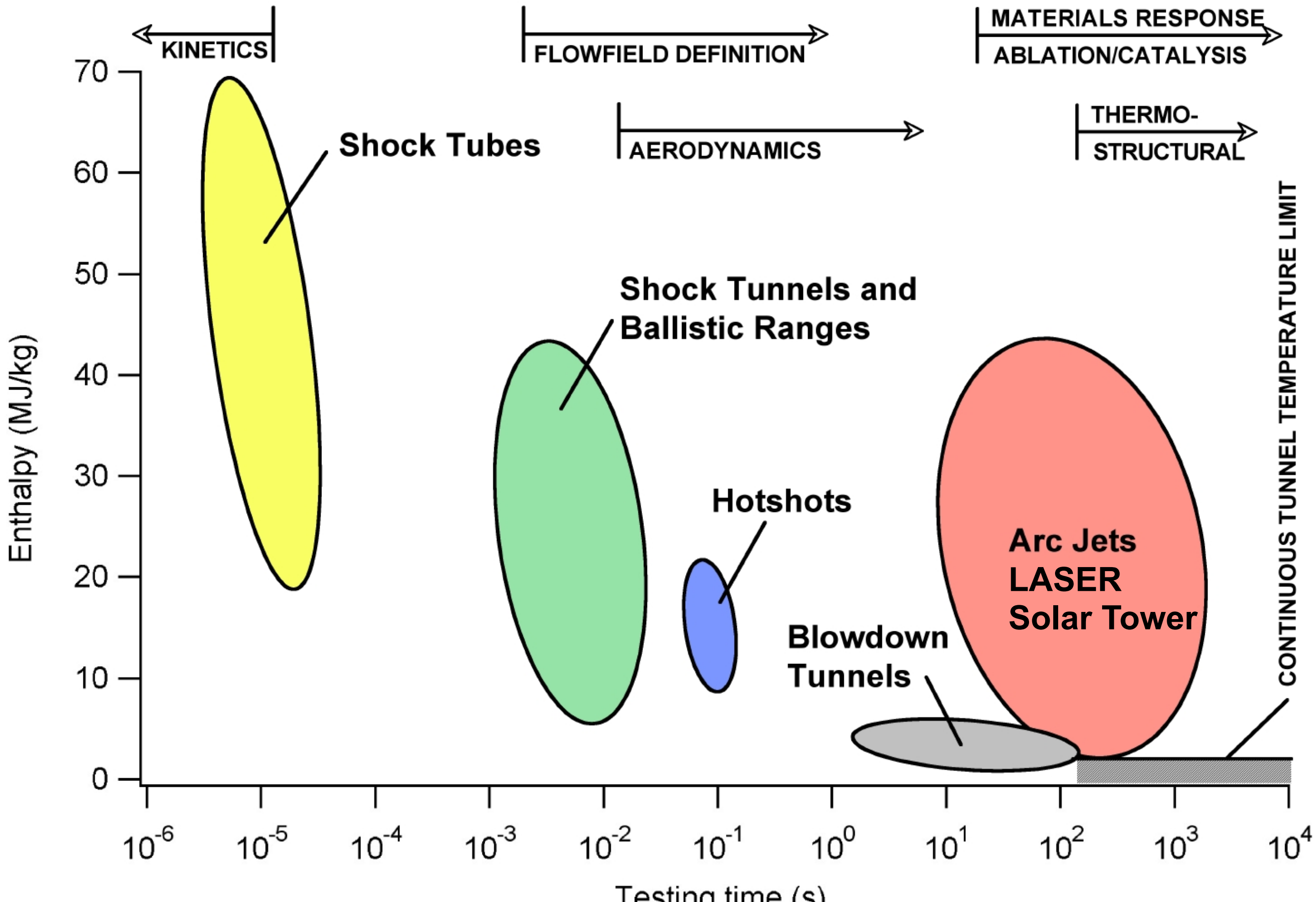
NASA/FAP

- The level of the heating is dependent on:
  - Vehicle shape
  - Entry speed and flight trajectory
  - Atmospheric composition
  - TPS material composition & surface properties

- TPS material response is highly nonlinear and depends on factors such as heat flux, pressure, shear, gas composition, etc

One cannot match size, density and speed in ground testing, so short of flight testing one cannot achieve the "test as you fly" paradigm

Ground Test Facility Types and Uses



Ground test facilities across various energy capability and test time are essential in characterizing the entry physics and TPS material response

TPS Piece-wise Certification

Objective: define heat flux failure mode boundaries

Test: High energy laser or solar facilities

Objective: acquire OML performance data (recession, catalycity, roughness, blowing, blockage and gaps)

Test: arc jet, shock tube, ballistic range

Objective: OML performance data with correct thermochemistry

Test: arcjet, ballistic range

Objective: Develop/ validate thermal response model

Test: arcjet, laser

<u>Piece-Wise TPS Design and Certification</u>

- No one facility can simultaneously duplicate the energy, boundary layer physics, heating and TPS chemistry experienced during actual entry
- Multiple test geometries and facilities must be employed within an anticipated vehicle entry space to design and certify TPS behavior and vehicle design
- This approach is know as piece-wise certification
- Has been used for entry vehicle design since days of Apollo

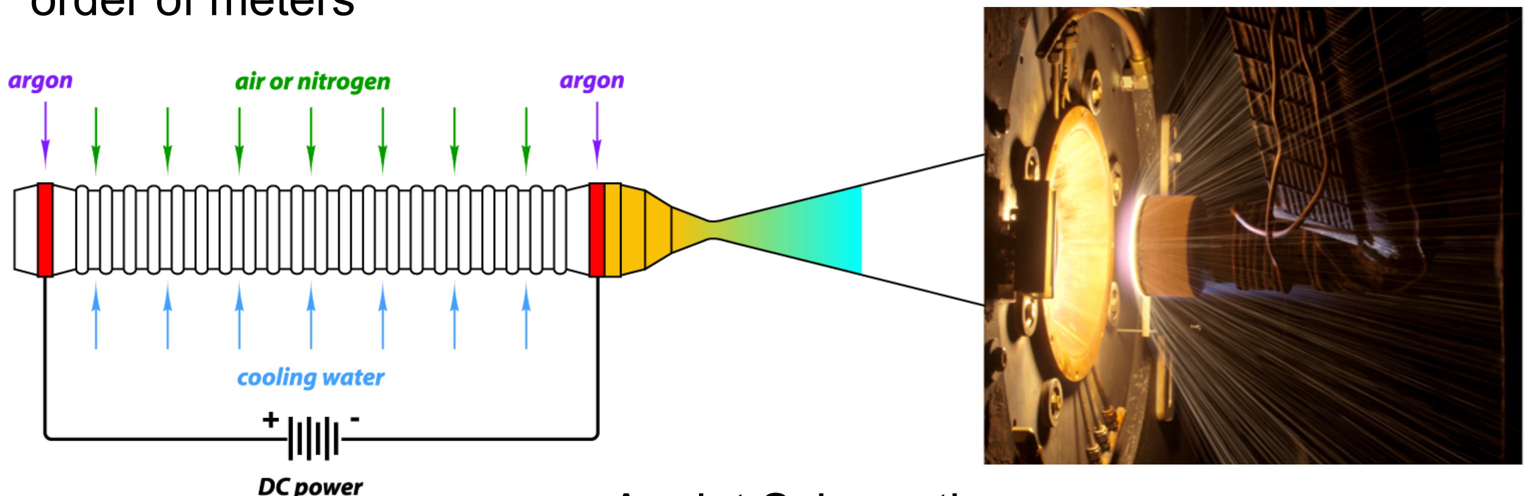
Arc Jet Testing
(Convective)

Sample Sizes 25-250mm

Arc Jets

Arc jets provide the best ground based simulation of flight in O_2, N_2, CO_2 for the purpose of designing and evaluating TPS response to entry

- Oxidation/ablation behavior on heating in static or flowing air at ambient pressures is likely to be significantly different than in a re-entry environment.
  - O_2 and N_2 may be dissociated
  - H/He was available in the 60's for Galileo testing, but no longer
- However, they cannot simulate all aspects of flight simultaneously
  - A matrix of tests is typically required to cover regimes of interest
  - Sample size is small (cm's) compared to actual vehicle that may be on the order of meters

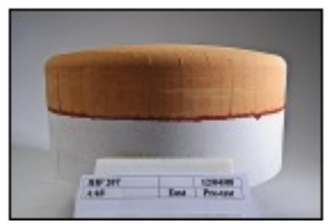


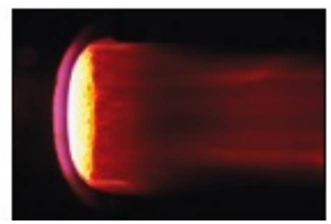
Arc jet Schematic

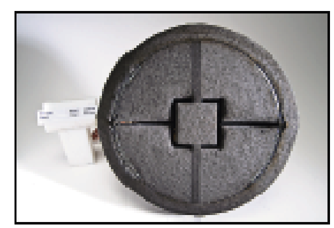
Arc Jets Cont.

Arc jets are capable of producing controllable and long duration high-temperature environments that simulate hypersonic entry

- Only 2 arc jet facilities exist in the US are capable of delivering sufficient power for high heat fluxes: ARC Interaction Heating Facility (IHF) and Arnold Engineering Development Center (AEDC)
- AEDC produces environments very high in pressure (~100 atm) as they do a lot of DoD RV testing
- Recently, IHF was upgraded to deliver both high heat flux (5000 W/cm^2) and high pressure (5-6 atm)

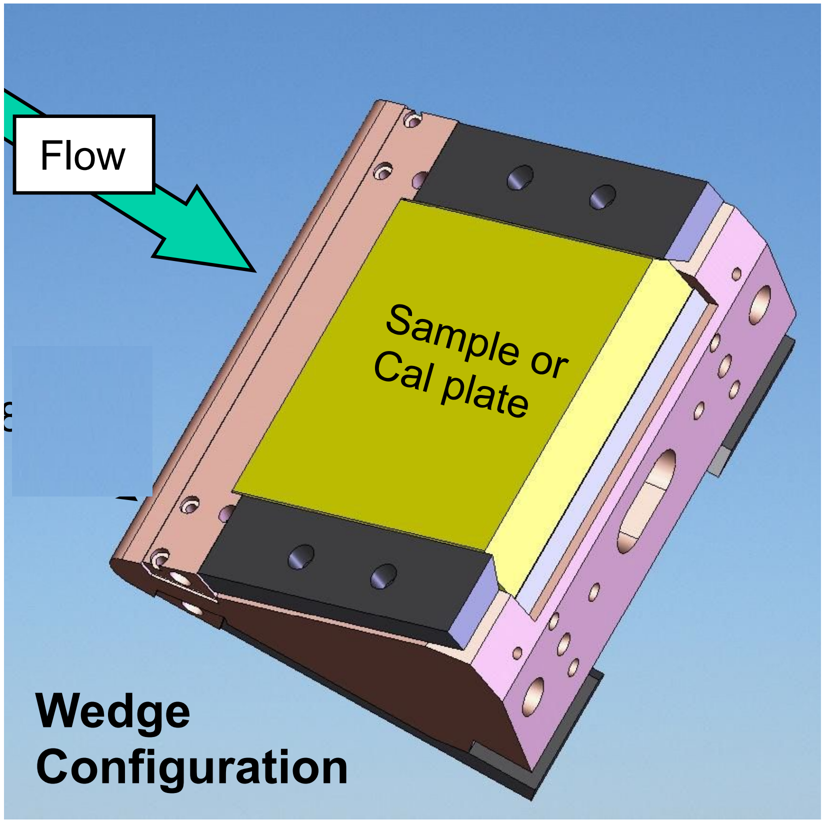






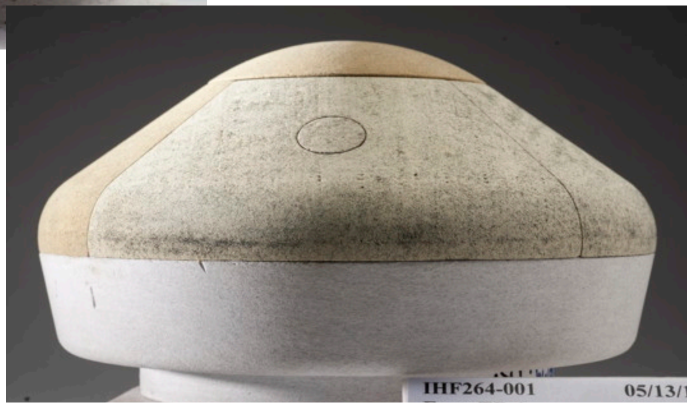
Shear Testing in an Arc Jet

- Well established shear test capabilities at ARC and AEDC through Orion and EDL Technology Development Projects
- CFD used to determine shear environment, cannot measure directly
- Shear configurations capable of experiencing shear levels from 200-4000 Pa depending on facility and model configuration



SPRITE Configuration

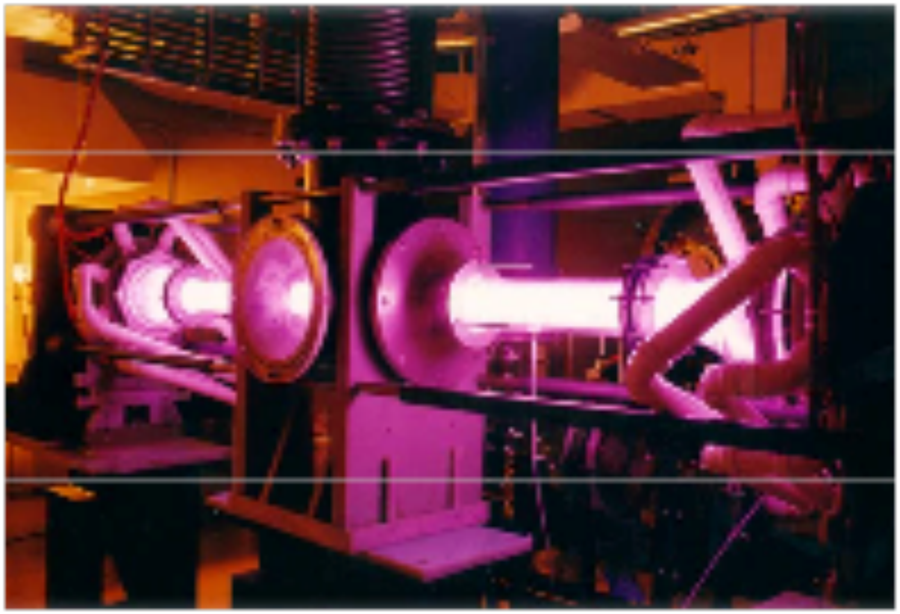
[1]Empey, D. M., Skokova, K.A., Agrawal P., Swanson G., Prabhu, D.K., Peterson K. H., and Venkatapathy E., "**Small Probe Reentry Investigation for TPS Engineering (SPRITE)**", proceedings, 8th International Planetary Probe Workshop, Portsmouth, VA, 6-10 June 2011.



Laser Testing
(Radiative)

Sample sizes 25-250mm

LASER Testing

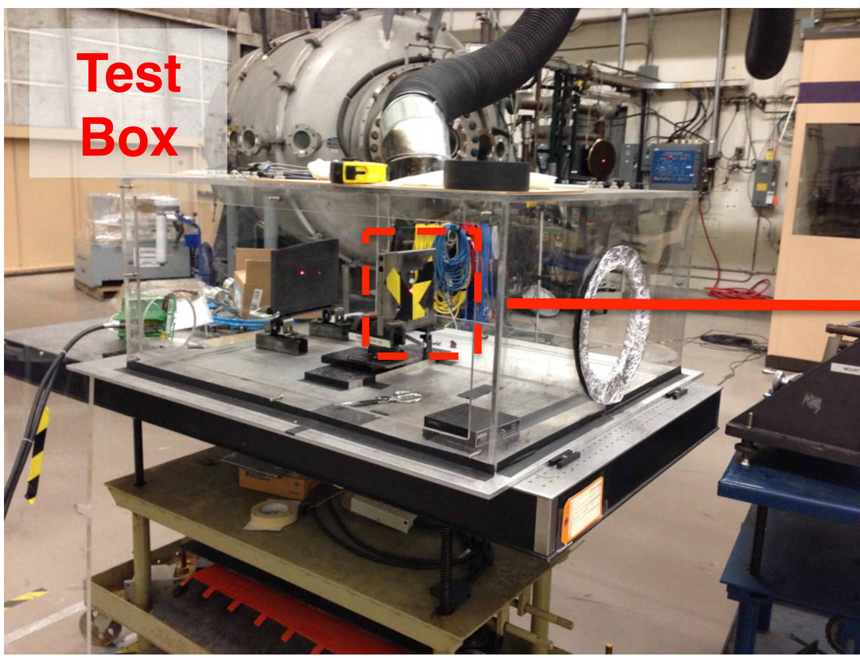


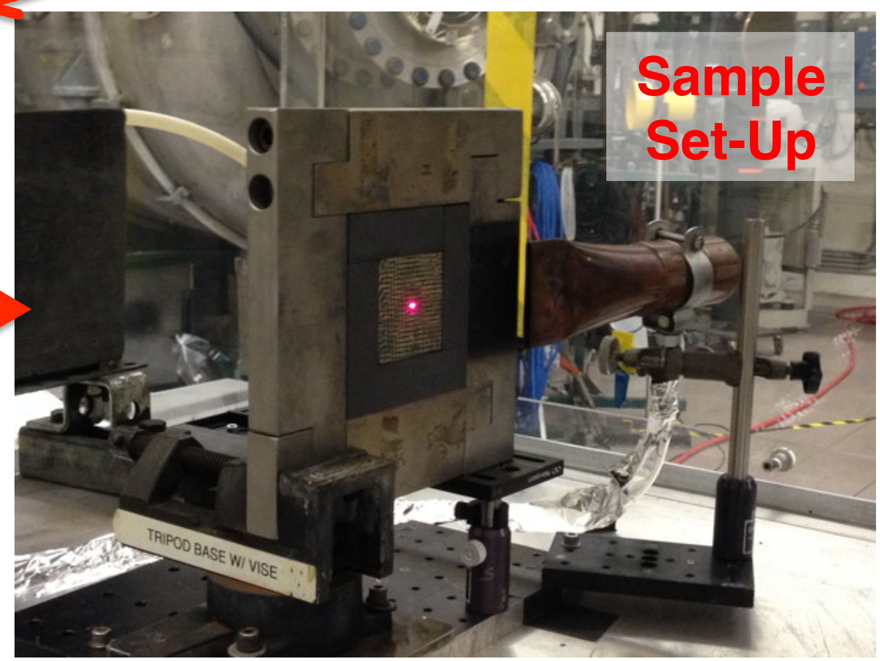
- Laser Hardened Materials Evaluation Laboratory (LHMEL) at The Wright Patterson AFB
  - Radiant heat source
  - CO_2 LASER, 10.6μm @ 1atm
  - 10 kW and 100 kW capability

- Tests can be run in a nitrogen purged test box to reduce oxidation, using N2 gas cross flow to reduce beam blockage by pyrolysis products

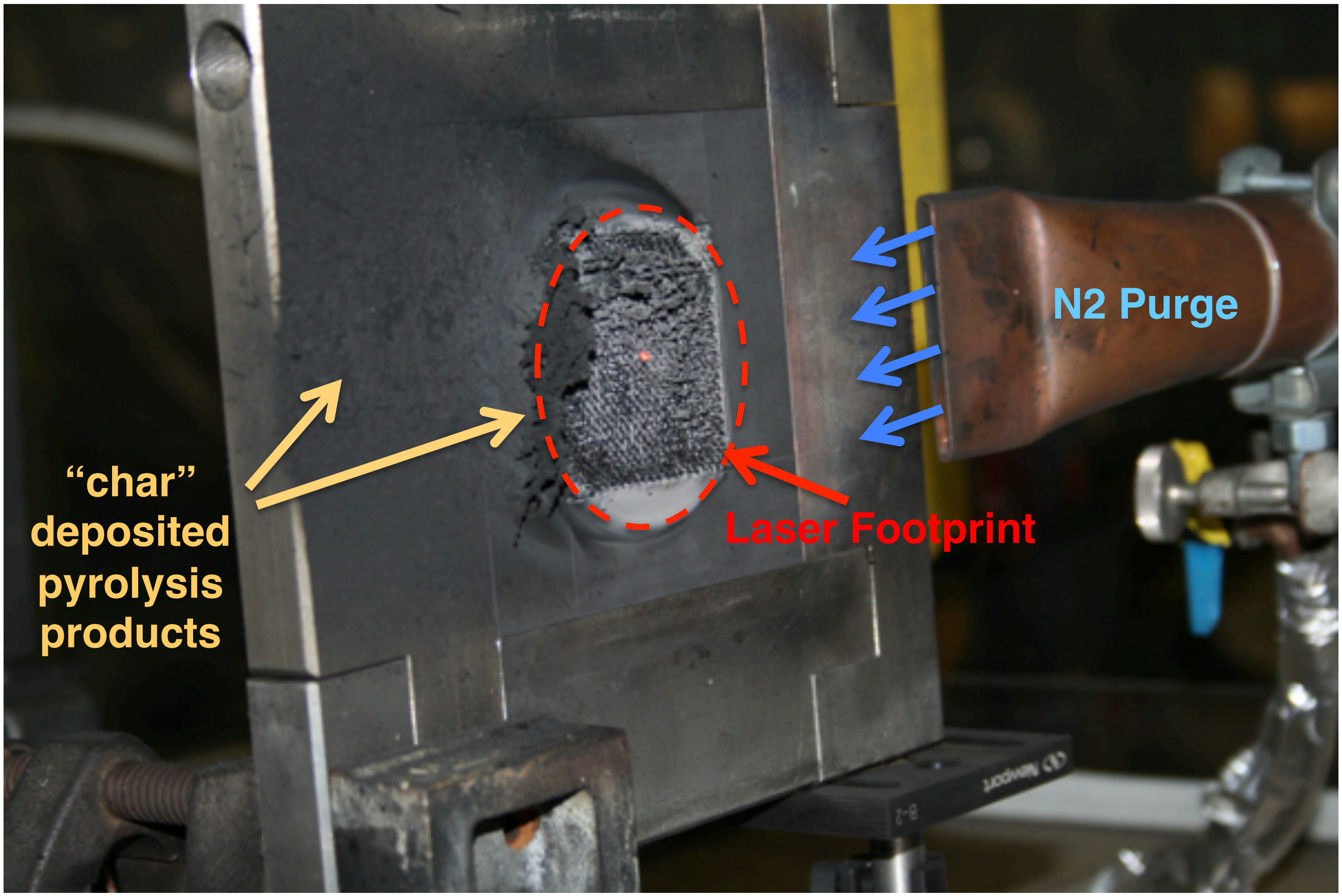
LHMEL facility allows for large test sizes and very high heating (8000 W/cm2) but facility operates at atmospheric pressure and produces little shear

LHMEL Facility





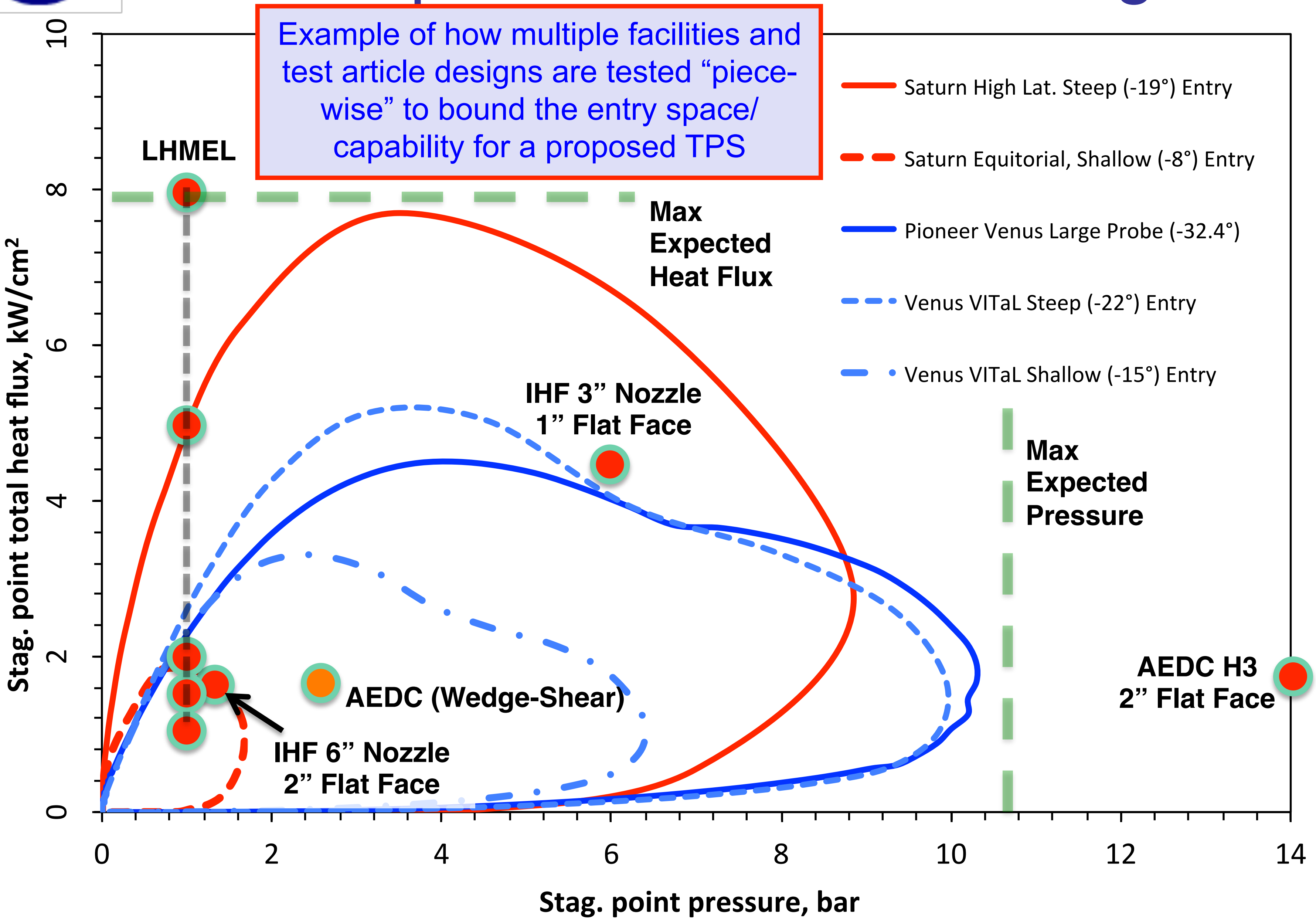
Post-Test Sample in Test Box



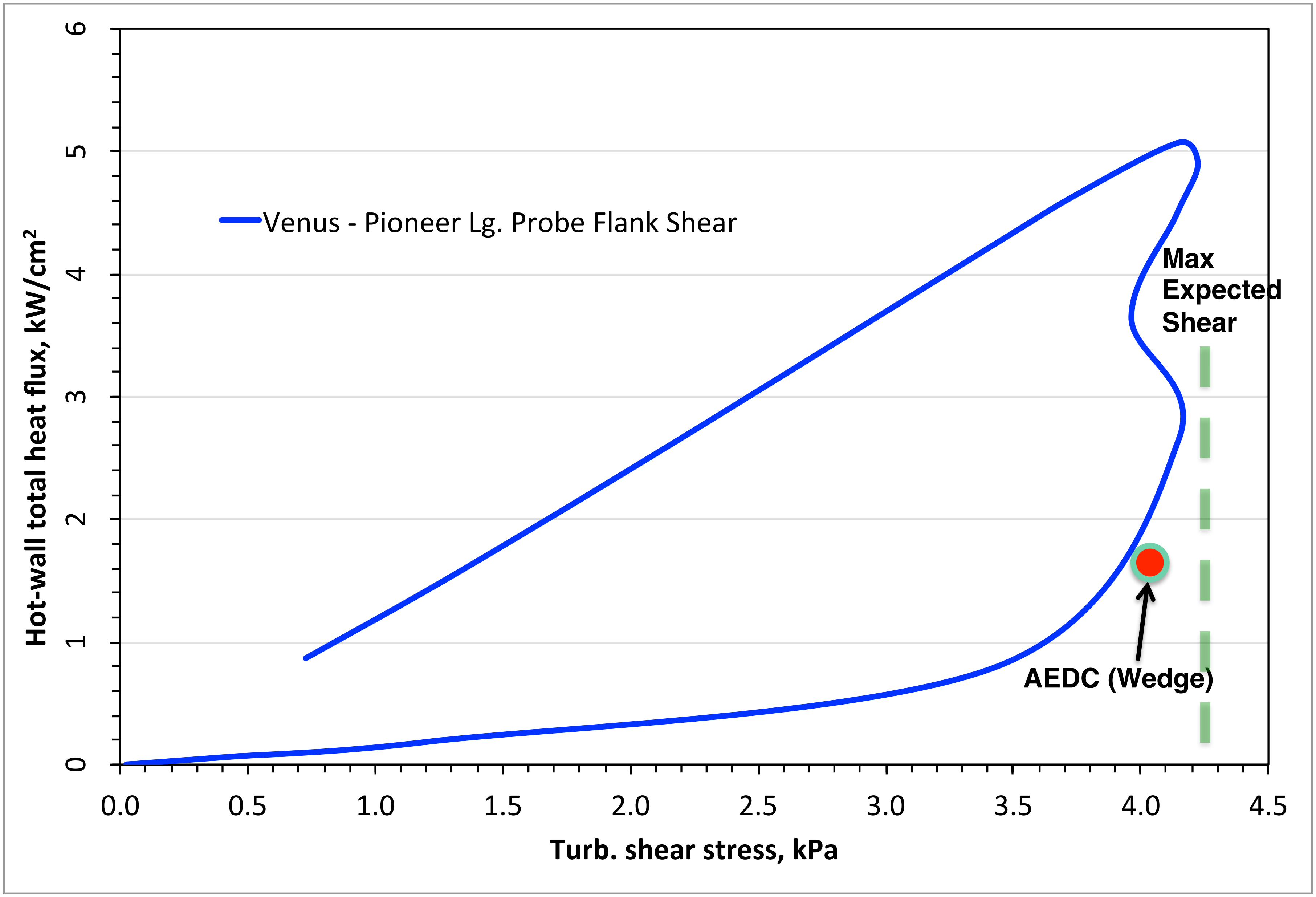
N2 purge gas used to push ablation products out of beam path and limit oxidation

Example: Piece-Wise Testing

Example of how multiple facilities and test article designs are tested "piece-wise" to bound the entry space/ capability for a proposed TPS



Piece-Wise Testing Cont.



Solar Tower Testing (Radiative)

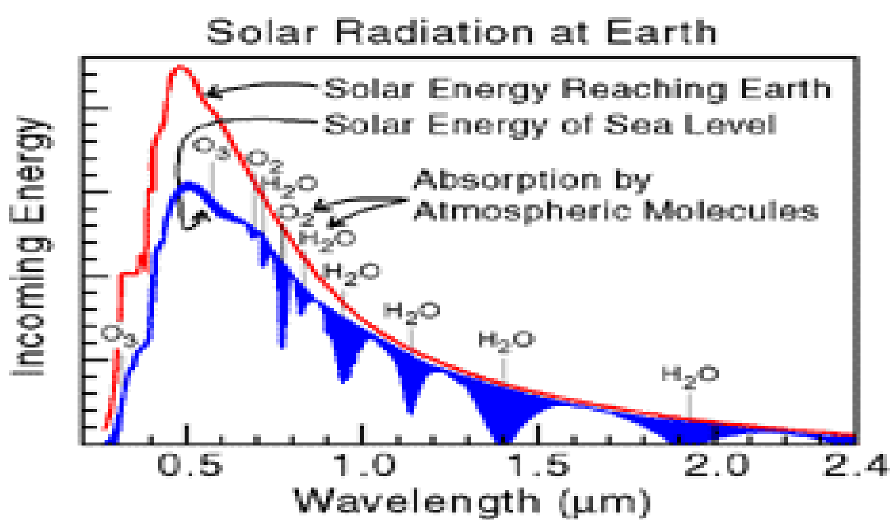
Sample Sizes 200mm to 1 meter+

Solar Power Tower

Solar Power Tower can test large articles 1m+ allowing for investigation of TPS interaction with attached aeroshell or sub-structure

- Smaller samples can be behind quartz window with nitrogen cross-flow, avoiding undesirable effects of wind and air
- Offers quick exposure control and long exposures
  - Heat flux capability: 300 W/cm2
- Broadband radiation with OK atmospheric absorption ~20% in NIR

ARA Ablative Labs testing of a 1m diameter aeroshell (150 W/cm^2)



Shock Tube
(Convective / Radiative)

Sample Sizes 10-25 mm

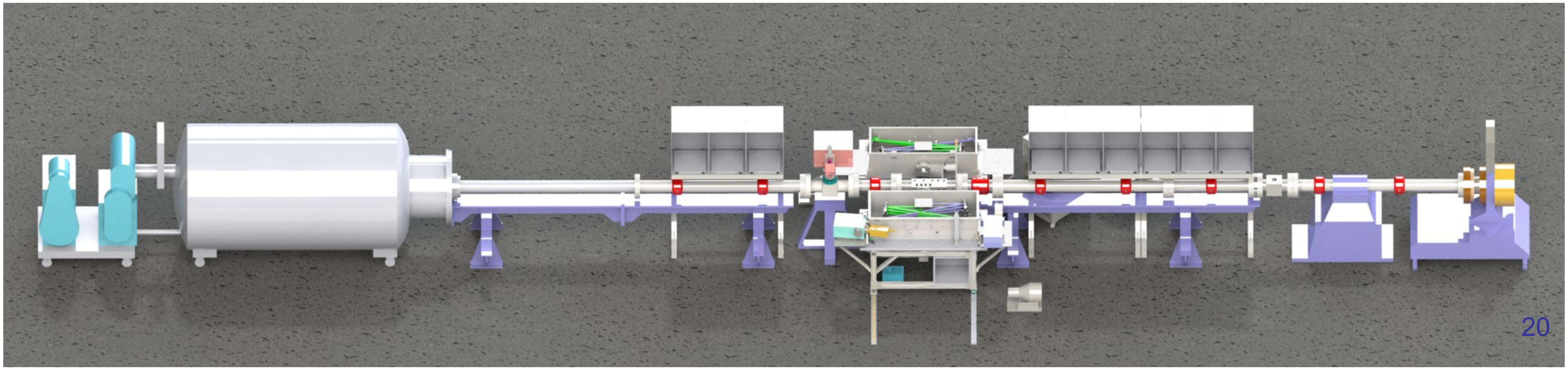
Electric Arc Shock Tube

The Electric Arc Shock Tube (EAST) is NASAs only capability of generating flight similar environments (simultaneous enthalpy, pressure and gas composition)

- Test times too short for material response studies
- Tests in EAST are essential for validating and building aerothermal models for radiative heating and boundary layer reaction kinetics

Example: SMD Outer Planets recently conducted a study of the impact of aerothermal uncertainties on entry heating predictions

- Saturn uncertainties in Convective Heating were ~6%, but Radiative Heating uncertainties were as much as 3x (8-40% of Total Heating)
- **Without these analyses, TPS may be under designed!**



Ballistic Range
(Convective / Radiative)

Sample Sizes 10-40 mm

Free Flight Ballistic Range

Designed to study entry probe aerodynamics and aerothermodynamics in relevant planetary atmospheres

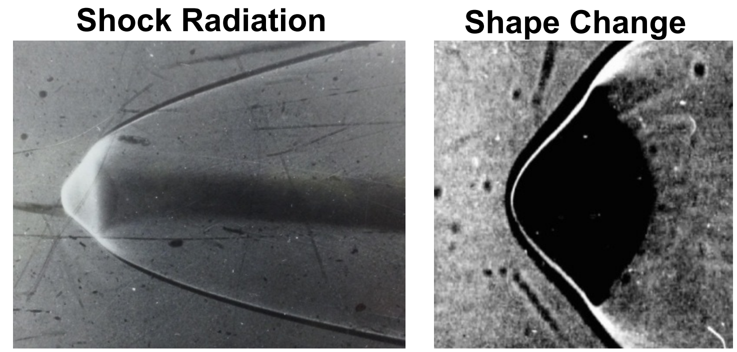
Model vehicles, fly from a gun at ballistic trajectories through an enclosed 34 m long range.

Performance Envelope:

Velocity:	0.2 km/s to 8.5 km/s
Static Pressure:	4×10^{-5} to 1 bar
Test gas:	Air, N_2, CO_2, **He/H_2**, Ar, etc.
Reynolds number:	0.03×10^6/m to 500×10^6/m
Max model dia:	0.038 m

Galileo Probe Free Flight Testing

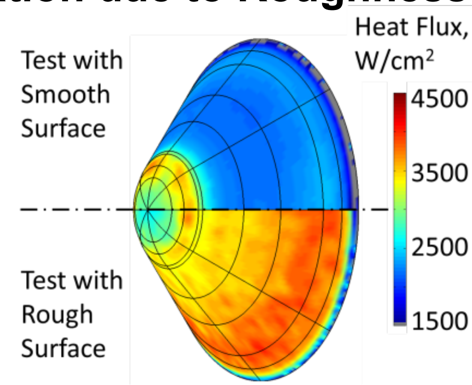
Shape change of carbon-phenolic models measured in high radiative heating environments (**1 MW/cm²** achieved by flight through Xenon)



Park and De Rose, NASA TM 81209

Heat Flux Augmentation due to Roughness

Effects of surface roughness on convective heating to probe geometries measured at various conditions and test gases



Wilder, Reda, and Prabhu, to be presented at the AIAA Aerospace Sciences Meeting, January 2014

Summary

- Atmospheric entry vehicles require thermal protection systems (TPS) because they are subjected to intense heating that is highly nonlinear
- Unfortunately, it is very difficult to match size, heat flux, pressure, shear, gas composition, etc. in ground testing thus one cannot typically "test as you fly"
- Various test facilities exist to bound the envelope of expected vehicle performance (Arc Jets, LASER, Solar Tower, Shock Tube, Ballistic Range)
  - Convective vs radiative heating
  - mm scale models to meter scale models
  - Stagnation vs shear (wedge or SPRITE)
- Piece-wise testing approach must be used across available ground test facilities to qualify/verify TPS performance and vehicle design